VARIATION IN THE HEAT EXCHANGE OF COMBUSTION PRODUCTS OVER AN OSCILLATION PERIOD DURING VIBRATIONAL FLAME PROPAGATION

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The heat fluxes from the combustion products to the pipe walls as a function of time are determined. Experiments confirm the physical mechanism suggested in the report for the variation in heat exchange over an oscillation period during vibrational flame propagation.

The effective employment of vibrational combustion has recently become an urgent task. In connection with the intensification of heat exchange in the vibrational mode of combustion it has become necessary to study heat exchange during vibrational flame propagation and to compare it with heat exchange during uniform propagation. For the solution of this problem it is important to clarify the character of the variation of the heat exchange over an oscillation period. In the literature, however, time-averaged heat exchange is usually considered. The variation of the heat exchange during an oscillation period remains unclear.

The heat fluxes from the combustion products to the pipe walls as a function of time over an oscillation period during vibrational flame propagation in a pipe are determined in the present paper.

In the experiments we used a brass pipe with a rectangular cross section of 12.5 × 28.5 mm^2 and a length of 60 cm, open at one end. A translucent section with a length of 10 cm was located in the middle part of the pipe. Mixtures of carbon monoxide and air were used as the combustible mixture. The mixture was ignited at the open end of the pipe. The experimental conditions made it possible to vary the amplitude of the oscillations and to fully damp them. Mixtures of 25, 32, 37, and 45% CO and air were studied. The combustion temperature lay in the range of 1600-2100°K. The flame propagation velocity varied in the range of 45-90 cm/sec and the velocity of the combustion products in the range of 190-450 cm/sec. The amplitude and frequency of the velocity oscillations lay in the ranges of 150-640 cm/sec and 156-194 Hz, respectively.

In order to make it possible to calculate the heat fluxes to the walls, one must know the temperature and velocity fields of the heat carrier. The temperature fields were obtained experimentally using an interferometer and motion-picture filming [1]. The error of the temperature measurement increases with temperature and comprises 1.3% for T = 2000°K.

The average velocity of the combustion products over the cross section relative to the pipe walls was calculated by the equation

$$v = v_{\text{fr}} \, (\eta_m \eta_T - 1) + \delta v, \tag{1}$$

obtained with the help of the continuity equation. The quantity η_m is determined from the equation for the chemical reaction while the remaining quantities are determined from the motion-picture frames. The correctness of Eq. (1) was tested experimentally using the method of trace particles. A demonstration of the possibility of using the method of tracks to determine the velocity field in the combustion products during vibrational flame propagation, a description of the experiments, and their results are presented in [2]. The velocities calculated by Eq. (1) agree well with the results obtained by the method of tracks. The error in a velocity measurement by the method of trace particles was 1% while the error in a velocity determination by Eq. (1) was about 2%.

The motion of combustion products during flame propagation in a pipe is nonsteady. In this case a general equation, obtained through integration of the energy equation over the

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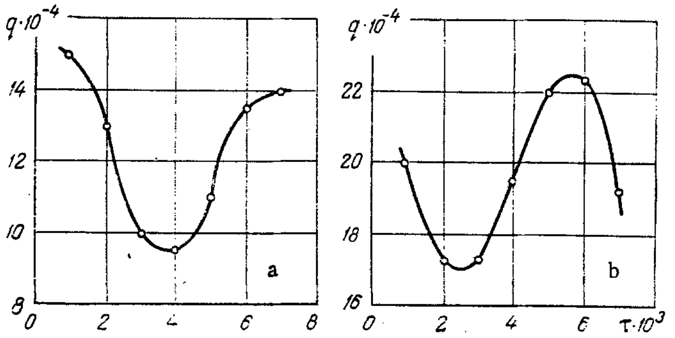

Fig. 1. Time dependence of heat flux for: a) a fixed pipe cross section; b) a fixed distance from the front (q, W/m²; τ, sec).

pipe cross section for an incompressible fluid with variable physical properties [3], is valid for the heat flux q:

$$q = \frac{1}{\chi}\left[\frac{\partial}{\partial\tau}\int \rho i dF + \frac{\partial}{\partial x}\int\left(\rho v i - \lambda\frac{\partial t}{\partial x}\right)dF - \int (q_v + \Phi)\,dF\right]. \tag{2}$$

An estimate made on the basis of the experimental data using an interferometer and motion picture filming showed that the quantity $[(\partial/\partial x)(\lambda\ \partial t/\partial x)]$ comprises a fraction of a percent of $(\partial/\partial x)(\rho v i)$. Therefore, the variation in heat-flux density along the axis due to heat conduction can be neglected. Because of the smallness we also ignore the heat liberated through dissipation. If, in addition, internal heat sources are absent from the stream (in the case under consideration there are none in the combustion products), then Eq. (2) takes the form

$$q = \frac{F}{\chi}\left[\frac{\partial}{\partial\tau}(\rho i) + \frac{\partial}{\partial x}(\rho v i)\right]. \tag{3}$$

Here the integrals are omitted and the integrands are taken as the average over the cross section. Equation (3) is reduced to the following:

$$q = \frac{F\rho_0 T_0}{\eta_m \chi}\left[\frac{\partial}{\partial\tau}\left(\frac{i}{T}\right) + \frac{\partial}{\partial x}\left\{\frac{i}{T}\left[v_{\mathrm{fr}}\left(\eta_m\frac{T}{T_0} - 1\right) + \delta v\right]\right\}\right]. \tag{4}$$

Here we use the relation

$$\rho = \rho_0\frac{1}{\eta_m}\frac{T_0}{T}. \tag{5}$$

The error in the determination of q by Eq. (4) was about 5%.

The tracks of the trace particles show the periodic variation of the velocity of the combustion products from minimum velocity as the flame front moves forward, when it is more extended, to maximum velocity as the front moves backward, when the front is less extended [2]. A periodic variation of the intensity of the circulating motion of the fresh gas directly ahead of the flame front was also detected in the experiments with trace particles.

The results of a computation by Eq. (4) of the heat flux in a fixed pipe cross section for different times during an oscillation period are presented in Fig. 1a. The heat flux varies periodically from larger values, when the flame front occupies positions closest to the given pipe cross section (times $\tau = 1 \cdot 10^{-3}$ sec and $\tau = 7 \cdot 10^{-3}$ sec), to smaller values, when the front occupies positions farthest from the given pipe cross section (time $\tau = 3 \cdot 10^{-3}$ sec). The variation of q is mainly due to the variation of the term $(\partial/\partial x)(\rho v i)$. The average value of $(\partial/\partial\tau)(\rho i)$ over a period is small and directly behind the flame front it comprises less than 10% of the average value of $(\partial/\partial x)(\rho v i)$ over a period. The sign of $(\partial/\partial\tau)(\rho i)$ varies in such a way that the quantity $(\partial/\partial\tau)(\rho i)$ smooths out the oscillations of $(\partial/\partial x)(\rho v i)$, as it were. But the influence of the term $(\partial/\partial\tau)(\rho i)$ grows with greater distance from the flame front. The pattern is repeated in subsequent cycles of oscillations.

Thus, the periodic variation of the heat transfer in a fixed pipe cross section is due mainly to the periodic variation of the distance from this pipe cross section to the flame front. Evidently, in an average over a period there would be no gain in heat transfer during pulsations in comparison with uniform propagation if the flame front did not change its shape and area. In reality, during vibrational propagation the flame front periodically varies its shape and area, and this is a cause of the variation in heat transfer over an oscillation period and at equal distances from the instantaneous position of the front. To clarify the physical mechanism of the variation in heat exchange during pulsations one must calculate the specific heat flux for different times during an oscillation cycle just at equal distances from the instantaneous position of the flame front. The results of such a calculation are shown in Fig. 1b. The specific heat flux q has minimum values at those times when the flame front is moving forward and has a more extended form (times $\tau = 2 \cdot 10^{-3}$ sec and $\tau = 3 \cdot 10^{-3}$ sec) and maximum values when it is moving backward and has a less extended form (times $\tau = 5 \cdot 10^{-3}$ sec and $\tau = 6 \cdot 10^{-3}$ sec). Concerning Fig. 1a, b, it should be said that a change in the composition of the mixture and in the amplitude of the oscillations leads to a change in the numerical value of q, but the character of the curves of the dependence of q on τ remains the same.

Observations of the process of propagation of the flame front by motion picture filming showed that during forward motion of the flame front its area is larger, it is more drawn out, the edges of the front make a smaller angle with the pipe walls, the intensity of the circulating motion in the fresh gas directly ahead of the flame front is higher, the velocity of the combustion products relative to the pipe walls is lower, and the thickness of the thermal boundary layer is greater. And, conversely, during backward motion of the flame front its area is smaller, it is less drawn out, its edges make a larger angle with the pipe walls, the intensity of the circulating motion of the fresh gas directly ahead of the flame front is lower, the velocity of the combustion products relative to the pipe walls is higher, and the thickness of the thermal boundary layer is smaller.

Consequently, the variation of the specific heat flux over an oscillation period is affected by the periodic variation of three factors: the degree of drawing out of the flame front, the intensity of the circulating motion in the fresh gas directly ahead of the flame front, and the velocity of the combustion products relative to the pipe walls.

NOTATION

V_{fr}, average velocity of the flame front over an oscillation period; η_m, ratio of number of moles of combustion products to number of moles of the initial combustible mixture; η_T, ratio of average over the cross section of the temperature in degrees Kelvin of the combustion products, moving with a velocity v, to the temperature of the fresh mixture; δv, variable value of oscillating velocity, equal to $\omega A_0 \cos\omega\tau$, where ω and A_0 are the angular frequency and amplitude of the displacement of the combustion products; τ, time; χ, perimeter of pipe; F, cross-sectional area of pipe; i, enthalpy; x, longitudinal coordinate; λ, coefficient of thermal conductivity of gas; t, temperature; q_V, amount of heat released by internal heat sources per unit volume per unit time; Φ, dissipation function.

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